# Modelling of a Hybrid Solar Panel with Solar Concentration

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***Abstract***

A hybrid solar installation equipped with a holographic concentrator allows converting the solar radiation into thermal energy and photovoltaic energy. A modeling of the different energy transfers and efficiencies is presented in order to estimate the influence on the collected energy of the parameters such as solar radiation, environmental temperature and characteristics of the various elements making up the sensor. The obtained efficiency of the hybrid solar panel is 63%. This analysis is the first step before the realization of an experimental facility and before a more detailed modelling.

***Keywords***

*Hybrid Solar Panel; Photovoltaic Panel; Holographic Concentrator*

## Introduction

The more convenient and promising system to generate electricity at the surface of Earth from the solar energy is the photovoltaic method using a direct transformation by solar panels. Currently, only 5% of the energy in Ukraine is produced by photovoltaic transformation because of its high cost, but it's an interesting solution for places distant of the distribution lines of electricity. However, the photovoltaic conversion is regarded worldwide as a way forward among the possible non-fossil energy resources. Intensive research is being conducted to increase the efficiency of photovoltaic cells. Although high efficiencies were obtained in the laboratory for space applications (40.8% Boeing-Spectrolab in 2008, 39.7% Full Spectrum, and 41% European FP-7 program Hiper 2009-2011), marketed solar panels have an efficiency only 19-20%. Nowadays, the radiation of the Sun to warm domestic water is currently used.

The solar panel previously developed in USA uses a separation of the solar flux by a holographic sheet to produce electricity by a photovoltaic panel. However, this solar panel does not use the thermal sun energy. Other hybrid panels with thermal and electric productions are currently proposed but without holographic separation. The originality of the presented research on a hybrid panel is found in the association of thermal and electric productions with holographic film.

In the studied solar system, the concentration of the radiation is performed by a holographic film set between two layers of polycarbonate. The solar radiation in the visible range (380nm-700nm) is partially reflected by the holographic film and after multiple surface reflections this radiation falls on the photovoltaic cells. The device combines the photoelectric cell and a heat exchanger that uses heat from the heating of solar cells and solar radiation that passes through the holographic film. The combined device offers the possibility to use the density of solar radiation per square meter with high efficiency. The steady state of the installation was modeled by introducing the intensity of solar flux, its reflection on the surface of the collector, the transmission in the polycarbonate, the properties of the holographic film, photovoltaic cell and heat exchanger. This simple model allows us to estimate the electrical and thermal performances of the installation. It is the starting point for a detailed analysis of this complex system. It will contribute to defining a final optimized system. The study will involve the definition of an optimal operating point of the solar panel for different conditions of solar flux, lighting change and temperature, taking into account the effect of partial shading. The modeling of current-voltage characteristics of the solar panel is necessary to optimize its design and is essential for the estimation of the performances according to its operating conditions.

## Set up

The spectrum in the visible range of the solar radiation is reflected on the holographic film and on the inner surface of the outer layer of polycarbonate monolith until it falls on the photovoltaic cell that produces electricity. The holographic film and the inner surface of the outer layer of polycarbonate monolith play the role in waveguides making a total internal reflection. The thermal radiation (IR range) crosses the holographic film and arrives on the thermal converter (absorber). A heat transfer fluid circulates in the tubes set in the absorber.

The main elements of the solar panel are a concentrator of solar energy (holographic film), a photovoltaic panel, and a thermal converter (FIG. 1).

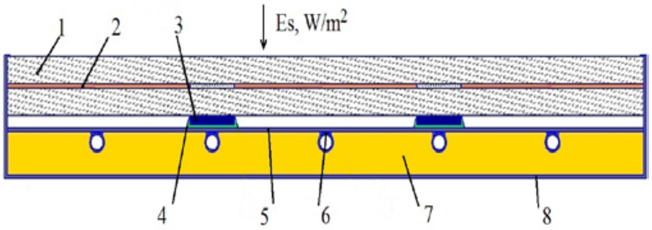
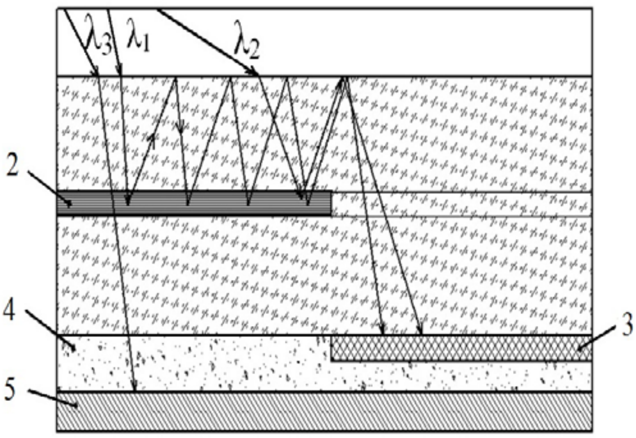



FIG. 1 HYBRID SOLAR SYSTEM

1. POLYCARBONATE MONOLITH 2. CONCENTRATOR OF SOLAR RADIATION – HOLOGRAPHIC FILM 3. PHOTOVOLTAIC CELLS 4. HEAT CONDUCTING GREASE 5. ABSORBER 6. HEAT TRANSFER FLUID 7. INSULATION 8. BODY

A thermal grease is necessary to deflect the heat energy arriving on photovoltaic cells in order to reduce the temperature of the photovoltaic cells and to increase its electric efficiency. The absorber is insulated to reduce heat losses to its external environment.




$\lambda_1$ $\lambda_2$ : VISIBLE SPECTRAL RANGE OF THE SOLAR RADIATION

$\lambda_3$ : THERMAL SPECTRAL RANGE OF THE SOLAR RADIATION

FIG. 2 TRANSMISSION OF THE SOLAR RADIATION

### *Holographic Film*

The used hologram is a medium with a three-dimensional holographic reflection that can restore the amplitude, phase and spectral composition of the object wave (Denisyuk hologram). Illuminated by a white light, it re-emits a radiation in a narrow range of wavelength which is close to that of the recording and which forms a holographic image. The radiation having a different frequency crosses the hologram without effect. The three-dimensional hologram effectively restores the image when it is illuminated with an angle adaptive to the wavelength used for recording. The brightness of the reconstructed image is maximum if the incident wave is illuminating the hologram with a Bragg angle which is a function of incident wavelength and the geometry of the registration system. A change in the wavelength modifies the angle at which all the reflected waves are added in phase. The three-dimensional hologram is obtained when the 3D interference figure is recorded and uses the entire depth of the recording layer. It is formed in the mass of the gelatine film as the systems of strata that the wavelengths used. The 3D hologram separates the solar radiation arriving on hybrid sensor into two spectral ranges: the visible range and the infrared range. This hologram serves as concentrator of the visible spectrum which reduces the amount of used photovoltaic cells.

The holographic film is composed of polyethylene-terephthalate and gelatin. It is covered with ethylene-vinyl -acetate (polymer glue).

### *Photovoltaic Cells*

The modeling was done considering AsGa solar cells from Spectrolab.

### *Polycarbonate Monolith*

Monolithic polycarbonate is used as protective cover instead of glass because of its mechanical properties which increases the lifespan of the installation because the monolith polycarbonate presents a resistance 250 times greater than glass. The polycarbonate monolith leaves from 88 to 93% of incident radiation (90-92% for the glass). Another advantage of the monolithic polycarbonate compared to glass is its density 50% lighter than glass, reducing the weight when the installation is placed on the roof of a house.

The polycarbonate is used as a waveguide for the transport of radiation which is reflected several times between the film and the polycarbonate-air interface

until it arrives on the surface of the photovoltaic cell, placed between the films. The critical angle of reflection between the monolithic polycarbonate (n=1.52) and air (n=1) is 39°. A total internal reflection requires an incidence lower than 39 °.

## Modeling

The different relations describing the behavior of the all sub-elements are briefly presented. The efficiency of the coupled thermal-voltaic solar device has been calculated to illustrate its advantages with the use of a set of parameters of holographic concentrator, photovoltaic and thermal device retained as an example to illustrate the advantages of the solar hybrid with holographic concentrator. The used model requires some assumptions as for the description of current-voltage relation of the photovoltaic cells, for the absence of heat transfer from the metallic box to the ambient atmosphere, for the values of the different heat exchanges parameters and for the use of a 1D description for the heat transfer (instead of 2D or 3D description). However, the presented model includes the main transfer to perform a first description of a hybrid solar captor.

### *Energy on the Photovoltaic Converter*

The solar radiation $\dot{E}_s(W/m^2)$ arrives on the surface of the captor and due to a reflection from this surface of the *U.V.* radiation, only $\dot{E}_0(W/m^2)$ enters in the solid polycarbonate layer (waveguide) and after it arrives on the holographic film with only a density per unit surface of $k_{op}\dot{E}_0(W/m^2)$ ($k_{op}$ is the optical coefficient of transmission of the polycarbonate layer). Then, the holographic film re-emits the energy $E_h(W) = k_h k_{op}\dot{E}_0 S_h$ where $k_h$ is the coefficient of emission of the holographic film having a surface $S_h$ ).

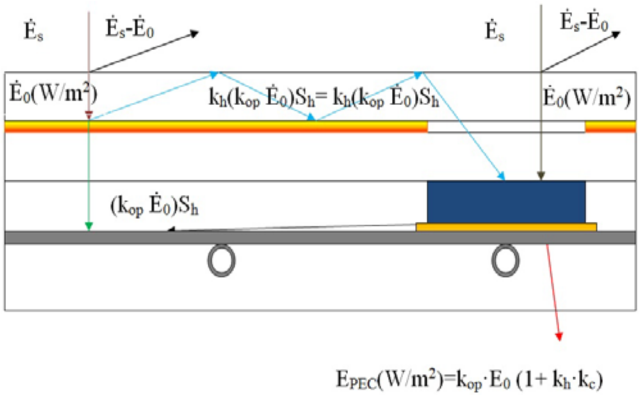



FIG. 3 ENERGETIC TRANSFERS IN THE SOLAR PANEL

The photovoltaic converter (surface $S_{PEC}$) receives the energy $E_h(W)$ reflected by the holographic film and the direct solar flux: $E_{PEC}(W) = k_h k_{op}\dot{E}_0 S_h + k_{op}\dot{E}_0 S_{PEC}$ . Taking into account the concentration coefficient $k_c$ related to the ratio of surfaces of the holographic film to the photovoltaic converter $k_c = \frac{S_h}{S_{PEC}}$, the density of radiation of energy $\dot{E}_{PEC}(W/m^2)$ influencing the surface of the photovoltaic converter (PEC) is:

$$\dot{E}_{PEC}(W/m^2) = k_{op}\dot{E}_0(1+k_h k_c) \qquad (1)$$

The different transfers of energy are shown on FIG 3.

### *Photovoltaic Current-voltage*

The characteristic voltage-current curve of the photovoltaic system is deduced from usual and simple relations describing the physical processes.

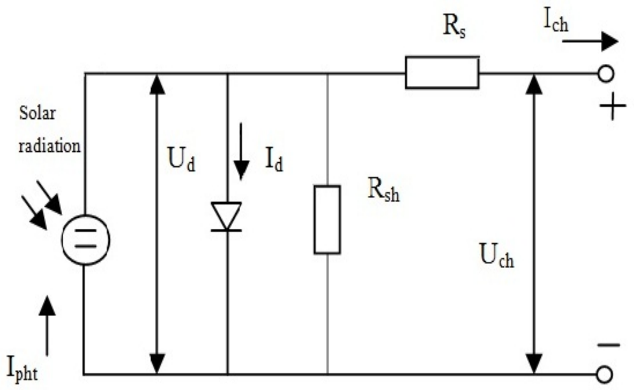



FIG. 4 SCHEMA OF THE ELECTRIC CIRCUIT EQUIVALENT TO A PHOTOVOLTAIC CELL

The photovoltaic system is described with the use of an equivalent schematic circuit which includes a resistance $R_s$ in series, a resistance $R_{sh}$ in parallel (shunt), a diode crossed by a current $I_d$, and a photo-current $I_{pht}$. Then, the characteristic current-voltage $I_{ch}$-$U_{ch}$ curve of photovoltaic system is written as,

$$I_{ch} = I_{pht} - I_0(\exp\left(\frac{q\cdot(U_{ch}+I_{ch}\cdot R_s)}{A\cdot\kappa\cdot T}\right) - 1) - \frac{U_{ch}+I_{ch}\cdot R_s}{R_{sh}} \qquad (2)$$

here $I_d$ is the diode current which is expressed as $I_d = I_0(e^{\frac{U_d}{V_0}} - 1)$, $U_d$ is the diode voltage as , $I_0$) is the reverse saturation current which is temperature dependent and $V_0$ is a diode parameter expressed as a function of the diode parameter A by $V_0 = \frac{AkT}{e}$ (k is the constant of Boltzmann, *T* is the temperature and e > 0 is the charge of electron). If one assumes that the

shunt resistance is large enough to neglect the last term in the relation (2), the current $I_{ch}$ becomes:

$$I_{ch} = I_{pht} - I_0(e^{\frac{U_d}{V_0}} - 1) =$$

$$= I_{pht} - I_0(exp\left(\frac{q \cdot (U_{ch} + I_{ch} \cdot R_s)}{A \cdot \kappa \cdot T}\right) - 1) \quad (3)$$

where the photovoltaic current $I_{pht}$ is the function of temperature $T$ by the relation:

$$I_{pht} = I_{cc}(\frac{\dot{E}_{PEC}}{\dot{E}_{0*}}) - dI_t(\frac{\dot{E}_{PEC}}{\dot{E}_{0*}})(T_{0*} - T) \quad (4)$$

The current $I_{cc}$ corresponds to nominal conditions with a density of solar flux $\dot{E}_{0*}(W/m^2)$ at the temperature $T_{0*}$ (short-circuit current), and $dI_t$ is a thermal parameter for the current. The relation between photovoltaic current and photovoltaic voltage is function of the solar radiation and temperature, and a set of parameters describing the behavior of the photovoltaic system ( $I_{cc}, R, A, T_{0*}, \dot{E}_{0*}, dI_t$ ). In this ideal model of Shockley, the diode parameters can be determined as on a basis of semiconductor structure voltage $U_{it}$ (which is the voltage when the photovoltaic circuit is opened $I_{ch}$ =0, $U_{ch}$ = $U_i$) as a function of temperature is expressed as:

$$U_{it} = U_i + dU_t \cdot (T_{0*} - T) \quad (5)$$

where $dU_t$ is a voltage temperature coefficient and $U_i$ is the floating voltage under the standard temperature $T_{0*}$ *(K)* and illumination changing. $U_i$ is depending on $I_{opt}$ and $I_o$, $U_i = \frac{Akt}{e} \cdot \ln\left(\frac{I_{opt}}{I_0} + 1\right)$. This relation allows us to calculate the parameter $A$ from the values of parameters $U_i$, $I_{opt}$, $I_o$ given by the manufacturer. From the physical characteristic (p-n junction), the resistance $R_s$ in series is given by:

$$R_s = \frac{U_{opt} + dU_t(T_{0*} - T)}{\left[I_{opt}\left(\frac{E_{PEC}}{E_{0*}}\right) - dI_t \cdot (T_{0*} - T)\right] \cdot r_d} \quad (6)$$

where $r_d$ = $dU/dI$ is a differential resistance at the beginning of illumination and $U_{opt}$ is a voltage at the optimal point. The reverse saturation current is temperature-dependent and deduced from the short-circuit condition

$$I_0 = \frac{I_{pht}}{exp\left(\frac{e \cdot U_{it}}{A \cdot k \cdot T}\right)}$$

where $T$ is the environmental temperature. The power delivered by solar energy plant is $P_u = \eta_{PEC}\overline{E}_{PEC}N_{PEC}S_{PEC}$ where $\overline{E}_{PEC}$ is a month-average, daily-average value of the energy of the solar radiation influencing the PEC's surface density (W/m²), where $\eta_{PEC}$ is the electric efficiency of the photoconverter, $N_{PEC}$ is the number of cells per unit of surface. The maximum power is given by $P_{max} = U_{opt}I_{opt}$.

### *Energy on the Thermal Converter*

The IR solar radiation arriving on the surface of the holographic film is $k_r k_{op}\dot{E}_0 S_h$ where the coefficient $k_r$ defines the IR energy in the solar radiation ($k_r$ = 0.47). If one assumes that this energy is transferred to the thermal converter, the energy $E^1_{th}(W)$ on the thermal system is $E^1_{th} = k_r k_{op}\dot{E}_0 S_h$. It is necessary to add the energy coming from the photovoltaic system. This energy is equal to the collected energy minus the energy converted in electricity is written as:

$$E^2_{th} = k_{op}\dot{E}_0 S_{PEC}(1 + k_h k_c)(1 - \eta_{PEC})$$

The total energy on the thermal system is:

$$E_{th} = E^1_{th} + E^2_{th} = k_r k_{op}\dot{E}_0 S_h + k_{op}\dot{E}_0 S_{PEC}(1 + k_h k_c)(1 - \eta_{PEC})$$

giving the following density of energy $\dot{E}_{th}(W/m^2)$:

$$\dot{E}_{th} = k_{op}\dot{E}_0\left[k_{s1}k_r + k_{s2}(1 + k_h k_c)(1 - \eta_{PEC})\right] \quad (7)$$

where $k_{s1} = \frac{S_h}{S_{th}}$ and $k_{s2} = \frac{S_{PEC}}{S_{th}}$ are ratios between the surfaces related to the surface of the thermal converter.

A schematic description can be used to describe the balance energy of the absorber. The received energy from the thermal converter is $\eta_0\dot{E}_{th}S_{th}$ if $\eta_0$ is the optical efficiency of the converter. Moreover, this energy is not completely given to the fluid due to the size of the calorific fluid circuit with a factor of exchange $F$. The thermal energy $Q_r(W)$ received by the fluid is $Q_r = FS_{th}\eta_0\dot{E}_{th}$. For the user, a loss of thermal energy is appearing in raison of the difference of temperature between the temperature of the fluid at

the exit of the solar captor and the ambient temperature $T$. This effect can be described by a loss of thermal energy as $Q_l = -\Lambda F S_{th}(\overline{T}_f - T)$ where $\overline{T}_f$ is the mean temperature of the fluid at the thermal converter enter. Then, the user receives the thermal energy:

$$Q = Q_r + Q_l = F S_{th}\left[\eta_0 \dot{E}_{th} - \Lambda(\overline{T}_f - T)\right] \tag{8}$$

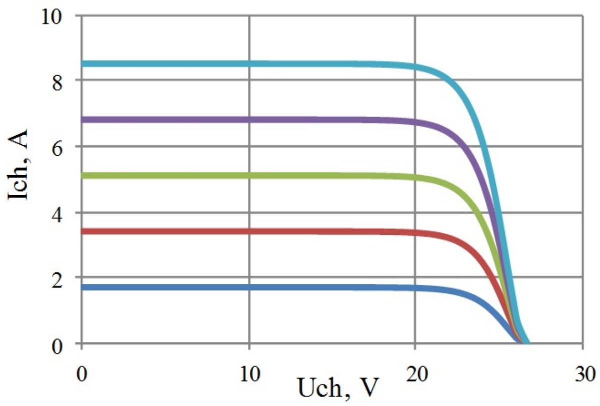
## Results for a Test Case

By way of example, numerical results are presented for a test case in order to illustrate the advantages combined receiver of solar radiation. The previous relations clearly indicate that the operating conditions of the captor are depending on many parameters: intensity of the solar radiation, sizes of the different elements, and their physical parameters. Typical values are retained.

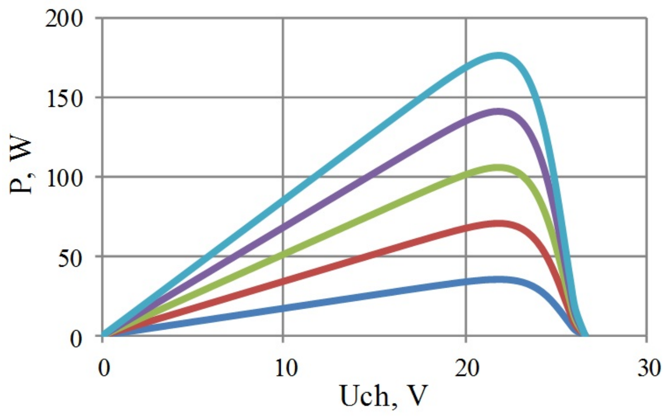
The surface of the combined receiver is *1 m²* and the surface of the photoconverter is 0.127 m². The incident solar radiation $\dot{E}_0$ is 1000 W/m² giving a density of energy $\dot{E}_{PEC}$ on the photoconverter of 7648 W/m² from the relation (1) with $k_{op}$=0.87 and $k_h$=0.97 and a density of energy $\dot{E}_{th}$ for the thermal conversion of 438 W/m² from the relation (7) with $k_r$=0.47, $k_{s1}$=0.873, $k_{s2}$=0.127, $\eta_{PEC}$=19% .

TABLE 1 PARAMETRE OF THE SOLQR CELL

| size | $U_i$ | $I_{cc}$ | $U_{opt}$ | $I_{opt}$ | $dI_t$ | $dU_t$ | $dP_t$ | $\eta_{PEC}$ |
|---|---|---|---|---|---|---|---|---|
| M | V | A | V | A | A/ degree | V/ degree | | % |
| 0.07x0.07 | 1.025 | 1.4945 | 0.9 | 1.4014 | 0.00098 | 0.0018 | 0.48 | 19 |




a)




b)

FIG. 5 CHARACTERISTICS OF THE PHOTOVOVERTER UNDER DIFFERENT SOLAR RADIATIONS $\dot{E}_0(W/m^2)$ EQUAL TO 200-400-600-800-1000 W/M² A) CURRENT-VOLTAGE B) POWER-VOLTAGE

The electric power delivered by the photoconverter is 235 W and the heat productivity of the solar collector is 388 W. However, the calorific fluid crossing the thermal converter will receive a lower energy due to loss of energy in the converter.

The characteristic curves voltage $U_{ch}$ - current $I_{ch}$ and voltage $U_{ch}$ - power $P = U_{ch}.I_{ch}$ of the photoconverter are presented on FIG. 5 for different values of the density of energy $\dot{E}_0$ from 200W/m² to 1000W/m². These curves present the classic behaviour of a photovoltaic converter with a quasi-constant value of the intensity as a function of the voltage $U_{ch}$ up a value of $U_{ch}$ independent on the energy and a fall to *0* for *2.7V* for the used values of the parameters. The electric power *P* presents a maximum for *22V* which is independent on the solar energy.

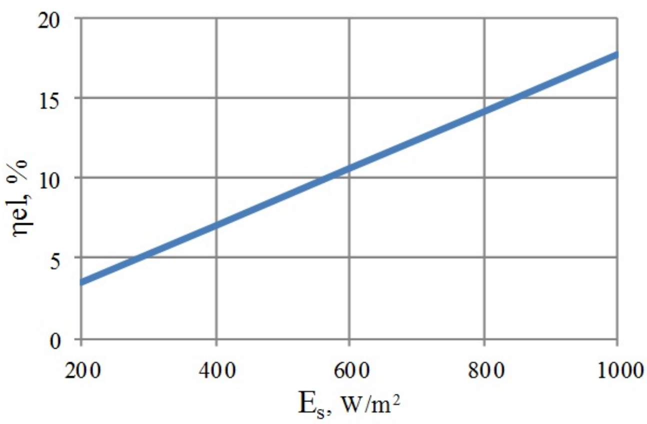



FIG. 6 EFFICIENCY OF THE PHOTOVOLTAIC SYSTEM

The collected thermal energy $Q$ has been estimated with $F = 0.9$, $S_{th} = 1m^2$, $\eta_0 = 0.87$, $\Lambda = 5$, $T = 301K$, $\overline{T}_f = 288K$, $\dot{E}_{th} = 87 - 438 W/m^2$ (FIG. 7). This energy is increasing

from 130W to 390W with a linear variation.

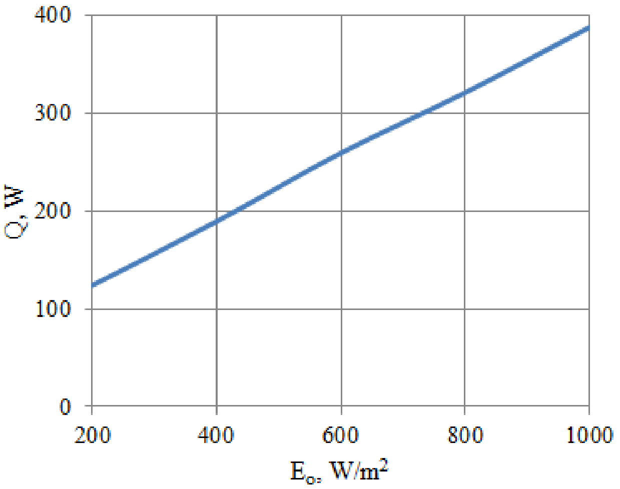



FIG. 7 THERMAL ENERGY AS A FONCTION OF SOLAR ENERGY

The photovoltaic cells have an electric efficiency written $\eta_{PEC}$ and another efficiency $\eta_{el}$ is defined. It is related to the global solar captor as $\eta_{el} = \frac{P}{S_{sc}\dot{E}_s}$ where $S_{sc}$ is the surface of the solar captor. The electric efficiency $\eta_{el}$ is a linear function of the energy and varying from 4% to 18% (FIG. 6).

The efficiency of the solar thermal converter is defined as $\eta_{th} = \frac{Q}{S_{sc}\dot{E}_{th}}$. This efficiency is a linear function of the energy and varies from 13% to 39% (FIG. 8).

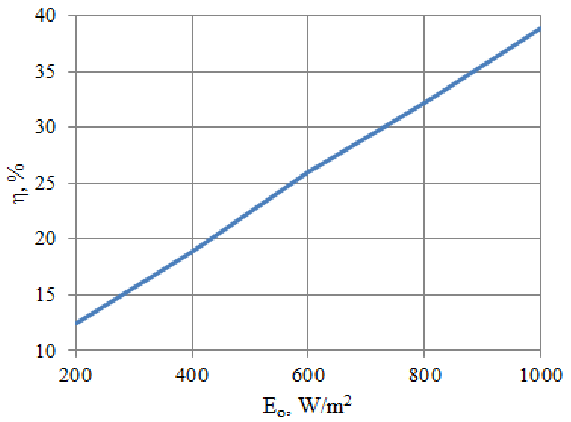



FIG. 8 EFFICIENCY OF THE THERMAL SYSTEM

The efficiency of the hybrid solar panel is:

$\eta_{ph} = \eta_{th} + \eta_{el} = 63\%$

## Conclusion

The modeling of the voltage-current and the voltage-power characteristic module determines the optimal operating point when the sun lighting and ambient temperature change. The characteristics of the hybrid solar system were deduced from the parameters of the solar cells from Spectrolab. The thermal heat delivered by the heat converter has been evaluated. The hybrid solar system provides electricity and heating. Such a system allows using solar radiation with a high efficiency, to reduce the size and weight. The proposed solar system can be used for "solar" homes.

It is obvious that the presented modeling of the thermal and electric transfers of energy is strongly depending on many parameters and requires an experimental validation, which is the next step of this study.

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**Sergii Gubin** was born December 5, 1958 in Kharkiv (Ukraine). Bachelor degree, specialist in Kharkiv State College of Ration Enginnering (1978). Master's degree, Electromechanical in National aerospace University "KhAI" (1984). Ph.D in National aerospace University "KhAI" (1998). He is Head of Department of Thrusters and Power Systems of Spacecrafts of the National Aerospace University "KhAI" and also is an associate professor of this department. He specializes in structures of autonomous and assured power supply systems, modeling of the processes in power supply systems of spacecrafts and plants of assured power supply, photovoltaic transformation of energy, electrochemical accumulation of energy, research of the processes in energy converters and accumulators. He has lectured over ten years at the National Aerospace University"Kharkiv Aviation Institute". In addition to working for the National Aerospace University, Sergey Gubin has participated in several research projects on demand of companies and industry leading enterprises of Ukraine and nearby countries, such as Central Specialized Design Office, Samara, Russia, Research-and-Production Complex "Saturn", Krasnodar, Russia, Design Office Department of Production Association "Kharkiv electrical equipment plant", Kharkiv, Ukraine, State Design Office "Yuzhnoye", Dnepropetrovsk, Ukraine, Institute of Semiconductor Physics of National Academy of Sciences, Kiev, Ukraine, Research Technological Institute of Instrument, Kharkiv, Ukraine. He has participated in the international research project "TEMPUS/TACIS".

**Michel Dudeck** was born August 9, 1945 in Paris. He obtained two PhD (1972 at the University Pierre and Marie Curie (UPMC) at Paris: Study of boundary layers in fluid mechanics, 1982 at the UPMC at Paris: State doctorate on Thermodynamics) and a Habilitation in 1987 at the UPMC. He is a professor at the University Pierre and Marie Curie (Paris 6) since 1988 and Assistant Professor from 1969 to 1988. He teaches Fluid Mechanics, Thermodynamics and Thermal systems. He was director of the French research group CNRS/CNES/SNECMA/Universities "Propulsion Spatiale par plasma " from 1996 to 2011. His research activity is carried out at the Jean Le Rond d'Alembert Institute at the University Pierre and Marie Curie. His research concerns the propulsion of satellites by Hall effect plasma thruster, plasma reentry in planetary atmospheres and thermodynamics of energetic systems (reverse osmosis, solar panels). Prof. Dudeck is member of the Societe Francaise de Physique (SFP) and the Association d'Aéronautique et d'Astronautique de France (AAAF).